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# USARIEM: Physiological Research for the Warfighter

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*The annals of military history are replete with graphic examples of the devastating effects of environmental factors on the outcome of battles, campaigns, and wars. From the catastrophic effects of the winter of 1775-1776 on the Continental Army, the Russian winter on Napoleon's Army in 1812, to the heat-related injuries or deaths in the Egyptian/Israeli war in 1967, heat, cold, and high terrestrial altitude have repeatedly played key roles in the success or failure of military operations. The U.S. Army Research Institute of Environmental Medicine (USARIEM) conducts basic and applied research to determine how exposure to extreme heat, severe cold, high terrestrial altitude, occupational tasks, physical training, deployment operations, and nutritional factors affect the health and performance of military personnel.*

## Introduction

A significant research effort involving more than 1 million Soldier participants at more than a dozen Army installations explored the relationships between measurable physical characteristics and health and performance outcomes, including physiological assessments, strength and endurance measurements, and disease epidemiology. It also evaluated the impact of rations and coffee on performance and injury in exhausting foot marches. Although this sounds like recent USARIEM studies, these studies were described by Benjamin Apthorp Gould in 1864, based on Union Army Soldiers. The point is that military operational medicine research, the kind of research conducted by the USARIEM has been of special importance to the U.S. warfighter since the early days of the Republic. These issues continue to be of great concern and will be as long as warfighters are challenged to the limits of their mental and physical capabilities in harsh environments. These limits of warfighter capability are ultimately determined by metabolic processes – it is the challenge of USARIEM to conduct the research to continue to define and expand these metabolic limits.<sup>1</sup>

The mission of USARIEM is to conduct biomedical research to protect the health and performance of Soldiers in training and operational environments. This largely involves “enhancement” of the Soldier capabilities by preventing the degradation of health and performance in the face of external stressors that may include the natural environment or manmade exposures, including our own materiel systems. This article outlines the core competencies and accomplishments of USARIEM and highlights the current and future goals of the research program for the warfighter.

## Capabilities and Approaches

The USARIEM is co-located with Natick Soldier Center

in Natick, MA. It is the modern day successor to elements of the Harvard Fatigue Laboratory, the Fort Knox Armored Medical Research Laboratory, the Quartermaster Climatic Research Laboratory (Lawrence, MA), the Arctic Laboratory, and the Fitzsimmons/Letterman Army Nutrition Labs.<sup>2,3</sup> The Institute has approximately 170 employees including 50 credentialed principal investigators; 65 of the staff are uniformed Soldiers, including 20 officers. The mix of specialties ranges from physiologists and psychologists to biomathematical modelers, dieticians, physical therapists, physicians, physician's assistants, and veterinarians. The unit is optimally sized to function as a single integrated laboratory although it is administratively organized into four science divisions and a research support division. The science divisions are centered on core capabilities that involve environmental stressors and/or stressor countermeasures product lines: thermal and mountain medicine; military performance (exercise and psychology); nutrition and metabolism; and biomathematical modeling and biophysics. Most research studies and Science and Technology Objectives ([STOs], formally recognized research programs intended to address an important Army problem) require teaming across divisions, which is readily accomplished in this moderately small and hierarchically flat organization. Research management principles are summarized in Table 1. Principal regulatory functions are accomplished by committee: to include human use, animal use, credentialing, and quality assurance. Collocation with other research functions related to individual Soldier equipment and rations at the Natick Army post, and proximity to many great academic and technology centers in the Boston area provides a vital multiplier ranging from access to technical libraries to the availability of a highly skilled talent pool. Specialized capabilities include heat and cold chambers, immersion pools, altitude chambers, animal research facilities, biomechanics laboratory, exercise physiology labs, an in vivo bone research lab, and multiple biochemistry wet labs. Off-site laboratories include: an exercise physiology lab situated in

Womack AMC, Fort Bragg, NC (the USARIEM Medical Research Unit – Fort Bragg), a laboratory facility on top of Pike’s Peak, CO, lab space in other laboratories such as a genomics laboratory at Brigham and Women’s Hospital in Boston, and direct support from key contractors, notably the Pennington Biomedical Research Center in Baton Rouge, and JAYCOR (TITAN) Corp in San Diego. The location near Boston permits strong collaborations with universities and high technology businesses concentrated in the area. Closely related research efforts also exist in military labs in Canada (DRDC-Toronto) and France (CRSSA, Grenoble). A new operational medicine research laboratory is just being formed by the Bundeswehr in Berlin.

Independent peer review is an essential part of the research process
Every study must be traceable to a relevant Army problem or program; even basic research must address a key technology barrier
Basic research is integral to a strong military physiology program, providing the scientific depth and intuition to address unforeseen problems and to make true advances
Opportunistic research needs to be carefully considered as it can produce high payoffs or major program distractions
Study priorities should favor our core strengths and rely on extramural partners in areas where we are not the recognized experts
Every study must culminate in an archived report, with open literature publications being most desirable

Table 1. USARIEM Rules of Research

The USARIEM vision is to transition biomedical research findings that are timely and practical to forces deployed anywhere in the world. The primary reason for the Army to have this intramural science capability with both uniformed and civilian scientists is to have experts dedicated to eliciting, conducting, harvesting, and translating relevant science that expands options for Army policymakers and combat and materiel developers. A reliable metric of in-house scientific expertise is peer reviewed publication, reflecting active involvement in leading edge science, full engagement with the larger scientific community, and actual productive work. The importance of publication to intramurally funded research cannot be overstated; if results of a study are not critically appraised and documented, the study essentially was never done and taxpayer dollars were wasted. In the past 5 years, USARIEM scientists averaged 2.2 primary publications per year, a high rate of productivity within the research community. While scientific publication is necessary, it alone is not sufficient to cross the completion line with Army research. Nobody else in the Army is expected to be reading the specialty journals or developing the subject matter expertise that is resident in USARIEM scientists. This experience must also be translated into direct benefits to the Army mission through

recommendations for policy and doctrine, guidance for materiel developers, and predictive models for training and mission planners. General categories of USARIEM products are listed in Table 2 and recent accomplishments for the Soldier are listed in Table 3.

<u>Provide recommendations for training policy and guidance</u> to enhance Soldier capabilities and reduce health risks ( <i>the Army may put young men and women in harm’s way, but recruits are expected to come home even better than when they left</i> )
<u>Develop preventive medicine guidance</u> to save Soldier lives and reduce lost duty time and medical costs, as well as ensure long-term health even after they leave the Army ( <i>the challenge is to implement and institutionalize scientific knowledge through practical solutions</i> )
<u>Provide design specifications</u> to improve individual Soldier equipment and rations ( <i>we don’t make the Soldier stuff; we make the stuff safer, more effective, and Soldier compatible</i> )
<u>Devise monitoring strategies and predictive algorithms</u> to prevent and detect performance decrements (which may also signal impending casualty risks) for Soldiers in training and in operational environments ( <i>we have better “prognostics and diagnostics” intelligence on our sophisticated vehicles than we do on the status of our own Soldiers</i> )
<u>Protect Soldiers and the Army mission from “good ideas”</u> that may harm Soldier health and performance ( <i>but be open-minded enough not to exclude surprising breakthroughs</i> )
<u>Protect against technological surprise</u> by conducting basic research to investigate and monitor all revolutionary ideas and to explore every potential advantage for the Soldier ( <i>“Intellectual capital becomes an important aspect of the future” – Ron Segal, DDR&amp;E, 2004</i> )

Table 2. Categories of USARIEM Research Products

## Recognized Science Leadership in Environmental Medicine

The USARIEM is internationally recognized as an authority in environmental medicine, with notable expertise in heat and dehydration. This evolved from classical studies on sweat responses and other desert adaptations, reflecting the Institute’s origins in the Harvard Fatigue Laboratory, the Armored Medical Research Laboratory at Fort Knox, and the Quartermaster Climatic Laboratory in Lawrence, MA.<sup>3</sup> There is no other federal agency with a strong core program in this area and USARIEM scientists routinely served as consultants for a wide variety of other agencies on issues such as workplace heat standards for NIOSH, orbiter re-entry thermal challenges for NASA, national recommendations on water intake requirements by the Institute of Medicine, position statements on electrolyte drinks and hydration for the American College of Sports Medicine, and normal ranges of hemoconcentration for the U.S. Anti-Doping Agency. The research of USARIEM scientists is among the most highly cited in the world community of physiologists. For example, last year, six of the 20 most highly cited environmental physiology papers were produced by USARIEM scientists.

*Solutions for the warfighter today based on subject matter expertise and testing*

Rifle recoil limits to allow testing of new high powered shoulder-fired systems

New TB MED to reduce physical training injuries

Altitude guidance for operations in Afghanistan

"Red zone" model for heat strain guidance in chemical threat risk assessment

Fitness tracking software tool for DOD demonstration project at Fort Bragg

*Tech base research advances for near term solutions (for example, STOs)*

Microclimate cooling strategies that reduce power requirements by >50%

Protein requirements for high activity and low calorie intake

Redeployment neuropsychological assessments and associations with in theater exposures

Warfighter Physiological Monitor – Initial Capability System

Tyrosine effectiveness in sustaining mental performance under intense stress

*Basic research to develop and harvest potentially revolutionary advances*

Friend-foe discrimination in fatiguing and distracting vigilance tasks

Genomic profiles of heat stroke injury

Mineral micronutrition (zinc) requirements to sustain immune function

Biomechanical influences on mechanisms of bone remodeling

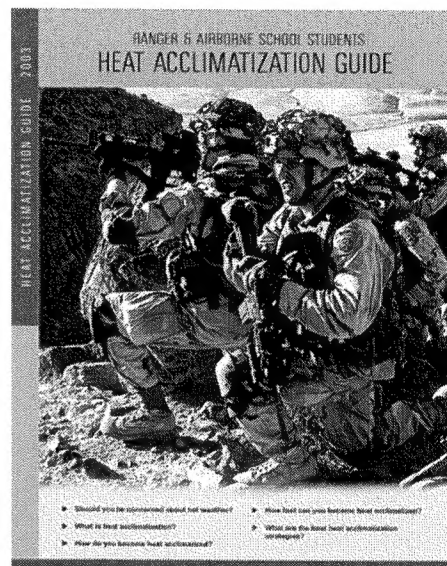
Insulin-like growth factor-I isoform responses to military operational stressors

*Table 3. What Has USARIEM Done for the Soldiers Lately ?  
Examples of Recent Accomplishments and Work in Progress  
(2003-2004)*

In WWII, Army physiologists developed simple methods for rapid heat acclimatization and this research was actually put to use on ships moving troops from the continental United States to North Africa in Operation Torch.<sup>4</sup> In the recent military actions in Southwest Asia, heat injuries were further minimized through hydration guidance as well as work-rest models that prevented unnecessary risk. Information was effectively distributed in 1991 through a pocket guide produced in a 1-week period by USARIEM scientists, as well as through new catch phrases to convey the knowledge (for example, "water as a tactical weapon"); in the past year, the most up-to-date science on acclimatization has been put into field guidance (Figure 1). Nevertheless, in 2004, Soldiers are still dying from heat stroke in both training and in deployments; these incidents were predictable and preventable with the available knowledge, indicating that we still have not been fully effective in translation of our knowledge into the protection of Soldiers.<sup>5</sup>

A new and relatively rare concern that surfaced in the past decade was a problem of excessive hydration and

hyponatremia, with training deaths caused by excessive water consumption. This led to new hydration tables with upper limits that were validated in hot weather training to ensure that the balance did not tip too far and lead to an increase in heat injuries.<sup>6</sup> Most recently, a program to enhance cooling efficiency with vasodilators, regional and intermittent cooling, and skin temperature feedback has produced a significant breakthrough that takes power-hungry microclimate cooling devices (for example, water-cooled garments) from interesting future concepts to power-efficient and effective near term reality.<sup>7</sup>

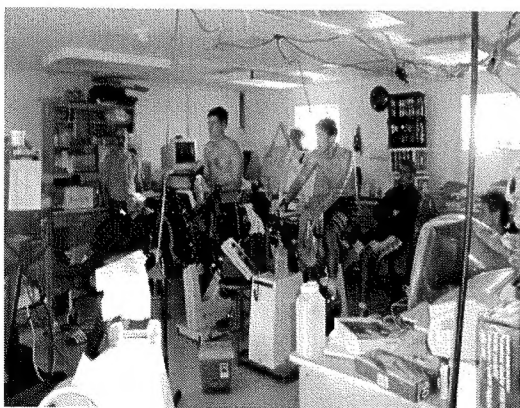


*Fig 1. Heat Acclimatization Guide 2003. This is an example of the information products produced for preventive medicine activities based on USARIEM research and subject matter expertise.*

Cold research is also conducted at USARIEM. It is an unfortunate reality that preventive medicine is most appreciated following failures, not after successes that ensure the absence of adverse events. It is especially unfortunate if the first disaster does not lead to a substantive solution. For example, the Army suffered a large number of cold weather injuries in the Aleutian Islands during WWII through cold wet exposures that occurred when landing craft fell short of the shorelines. These high casualty rates against enemy forces that had already withdrawn reflected a gross underestimation of environmental risks. In 1976, hypothermia deaths in the swamp phase of the Ranger training school led to a comprehensive revision of the course and new immersion cold exposure tables from USARIEM based on best available data. In 1995, more hypothermia deaths in Ranger training led to new studies at USARIEM that have revealed previously unknown effects of repeated cold exposures and important interactions with other stressors that explain the occurrence of hypothermia at relatively mild water

temperatures.<sup>8</sup> Exposure guidance has again been revised based on these new findings and with new models developed in conjunction with expert colleagues at USARIEM's Canadian counterpart, DRDC-Toronto.<sup>9</sup> This knowledge has been captured in a new TB MED on cold injury prevention.

There is a much lower tolerance for risks in training than there is in operational emergencies where a commander may not have a choice in the assumption of risks; however, in either case, commanders need accurate assessments for their mission planning. In recent operations in Afghanistan, commanders knew that there were health and performance risks associated with rapid ascent to well over 10,000 ft in the Spin Ghar mountain range and they needed quick advice on how to best mitigate the risks. The USARIEM was the only institution in any federal agency that could provide this immediate expertise on what to expect and how to best prevent and treat problems with high altitude illnesses.<sup>10</sup> Soldiers were acutely impaired, where a 50 pound load felt like 100 pounds for unacclimatized troops reaching 10,000 ft, and at least one serious accident occurred in a helicopter evacuation of a suspected high altitude pulmonary edema emergency which may have been misdiagnosed. The special operations forces and the Army have both sponsored new efforts at USARIEM to develop rapid acclimatization strategies with intermittent hypoxia, explore nutritional supplements to boost performance at altitude (notably carbohydrate), and construct staging tables to provide recommendations on rates of ascent (similar to the concept of Navy dive tables). The USARIEM John Maher laboratory facility on top of Pike's Peak at 14,100 ft is currently the site of an important experiment to assess the relative advantage of having troops preacclimatized for rapid deployment to altitude, for example, mountain troops stationed at Fort Carson, CO (Figure 2).



*Fig 2. USARIEM Maher Laboratory on Pike's Peak, CO, at 14,100 ft. A current STO effort is collecting data from partially acclimatized individuals to determine how important this advantage is to rapid ascent in a military deployment.*

Future advances are expected to emerge from current basic research investments in environmental physiology to include genomics research assessing the human building blocks of environmental injury susceptibilities, a joint effort by USARIEM scientists and the genomics laboratory at the Brigham and Women's Hospital in Boston.<sup>11,12</sup>

The natural environment is not the only source of important interacting stressors that can threaten the health and performance of a Soldier in training and operational environments. The key stressors that USARIEM studies (some in collaboration with WRAIR) are listed in Table 4, with highlighted blocks for current areas of concentration.

#### **Prognostics and Diagnostics to Prevent Soldier "System" Failure**

Army vehicles are instrumented and monitored to an unprecedented degree as part of the "prognostics and diagnostics" strategies that allow them to keep running trouble-free for thousands of hours with only periodic maintenance. We have no comparable system for Soldiers even though existing technology makes the sensor engineering portion of this feasible today. The concept of physiological status monitoring of Soldiers provides one of the truly revolutionary breakthroughs in individual Soldier enhancement. Biotelemetry has been available for many years, ranging from sports watches for heart rate monitoring to patient instrumentation used in an intensive care ward. The novel technology is usually not the sensor, it is the algorithms that turn sensor data into useful predictive information. No one can glean much useful information from hundreds of raw heart rates streaming into a computer, but it would be immensely useful for a team leader or medic to access a signal that warns of an individual or a team headed for trouble based on a transparent algorithm that draws on combined sensor responses with high predictive reliability.<sup>13</sup>

The USARIEM is the center of this activity on Warfighter Physiological Status Monitoring. The near term initial capability version ("WPSM-IC") is part of an effort that requires building a self-sufficient prototype system to include sensors, integrating hub, and any needed communications, since no Soldier system is currently available to provide this engineering backbone for field validation tests. This WPSM-IC will have early version capabilities for live-dead detection, fatigue prediction from recent sleep and activity, heat strain predictions from heart rate and skin temperature, and hydration predictions from instrumented water intake measures (Figure 3). This "sensor suite" capitalizes on the most developed physiological models in sleep and fatigue from WRAIR and in heat and hydration from USARIEM.

	Countermeasure Product		
Stressor/Exposure	Training and Acclimatization	Nutrition and Metabolic Regulation	Models on Human Limits and Effects
Heat	Acclimatization markers (STP 3.T)	Water metabolism (STO 3.T)	Predictive algorithms (STO 3.H)
Cold		Tyrosine supplement (STP 3.I)	Exposure tables (STP 3.I)
Hypobaric Hypoxia	Rapid acclimatization (STO 3.J)	Carbohydrate supplement (STO 3.J)	Staging tables (STO 3.J)
Physical work	“Smart” training (STO 3.S)	Weight management (STP 3.O)	Neck fatigue model (STO 3.Z)
Energy deficit		Protein requirements (STO 3.B)	Energy bal measures (STP 3.H’)
Biodynamic forces	Bone remodeling mechanism (STP 3.S)	Bone mineral accretion (STP 3.S)	Body armor eval STO 3.K (JAYCOR)
Neurotoxic chemicals*		Antioxidant supplement (Future)	Neuroepidemiology STP 3.M
Sleep deficit		Carbohydrates and caffeine (STP 3.B’)	Fatigue-performance STO 3.Q (WRAIR)
Anxiety and fear	Stress resilience STO 3.W (WRAIR)	Stress markers (STP 3.B’)	

\*Oxidative and inflammatory stressors

Note: Shading indicates areas of current USARIEM focus, with darkest indicating greatest investment; STOs are Science and Technology Objectives – programmed research approved by Army; STPs are Science and Technology Evaluation Packages – programmed research approved by the USAMRMC.

The focus of the research is on solving Soldier problems that almost always involve more than one stressor in field environments and where the interactions of stressors may be critical, such as sleep at altitude, changes in toxicity of materiel in the heat, work in a hypocaloric environment, etc.

Table 4. Environmental and Occupational Stressors Studied at USARIEM and Associated Laboratories

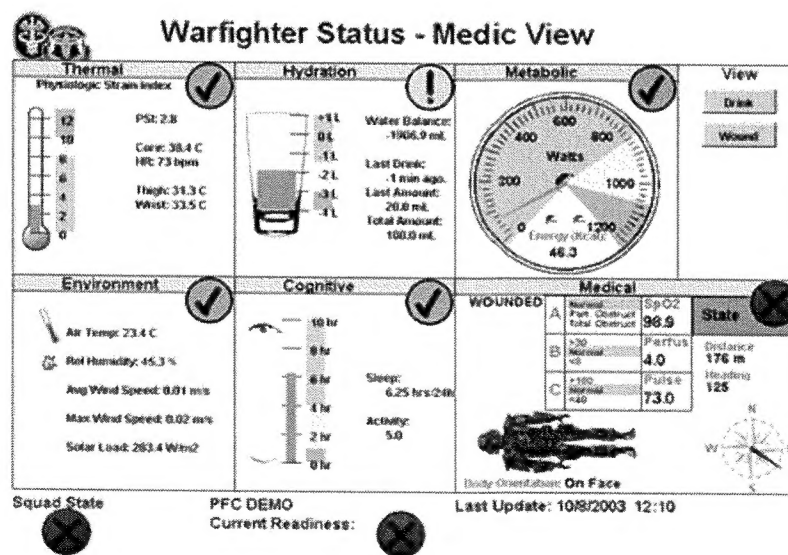


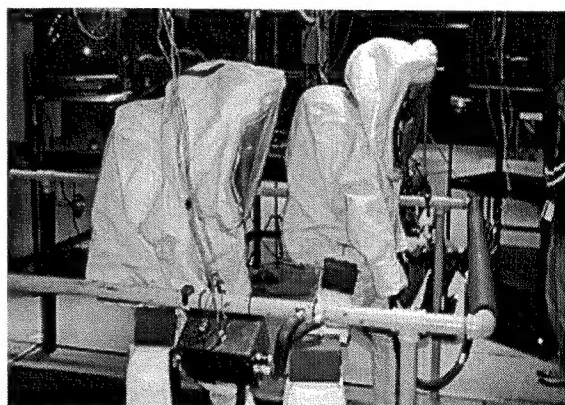
Fig 3. Notional Soldier readout presenting real time information on physiological status based on models and algorithms that interpret Soldier sensor data. In this example, hydration is low based on recent water consumption history and the prone Soldier may be casualty.

Future versions (for example, "WPSM-Commander") will provide enhancements that include estimates of energy flux ("fuel tank and RPM" equivalents), other environmental risk predictions ("engine temperature and oil level" equivalents), and improved real time analyses that include comparisons to ambient conditions, comprehensive Soldier databases and models, and individual Soldier history. Vital relevant information to a commander on a Soldier's mental status will be predicted from a minimal sensor set that might involve noninvasive measures such as nerve conduction velocity, eye movements, voice stress analysis, and Soldier task-embedded metrics, as well as improved neuropsychological predictions derived from environmental conditions and other status information. The greatest value for these sensor systems may be in training, where commanders and units learn their true limits before impending failure; however, plug-and-play systems tailored to a variety of specific mission requirements will undoubtedly find their way into every conceivable application. The goal of this monitoring is to help Soldiers effectively achieve the full range of their physiological capabilities, just as an athlete training to target heart rates or blood lactate levels uses physiology to achieve peak performance. From a USARIEM perspective, this is an opportunity to gather years of physiological data and algorithms into a useful integrated application for the Army.

Another example of a potential future system diagnostic/prognostic component is energy balance. Energy balance is an important physiological measure that may predict falling glucose levels that affect mental performance, limit physical endurance, predict impaired shivering thermogenesis, or predict the rate of heat storage. The USARIEM scientists have devised various methods to noninvasively assess voluntary energy expenditure based on biomechanical principals that can be incorporated into a "smart" boot that measures foot contact time.<sup>14</sup> This can even be combined with heart rate measures to provide an assessment of aerobic fitness level that might eliminate the need for periodic fitness testing for the future Soldier and help individuals in effective weight control.<sup>15</sup>

Another USARIEM diagnostic/prognostic tool is a heat strain monitor, a generational advancement of the old Wet Bulb Globe Monitor. Again, the main challenge is not in new discoveries for the hardware development, but in the advancement of research models that transform available data into useful knowledge. The algorithm used in a handheld USARIEM Heat Strain Monitor (with a version currently in use by the Australian mining industry) is an example of the applications that can be rapidly derived from a family of detailed and complex heat physiology models that have been developed through years of Army research.<sup>16-18</sup> Current efforts at USARIEM will merge location, Air Force weather data, and individual Soldier data to produce local environmental strain

predictions (for example, fluid intake requirements, work/rest cycle recommendations). Even the interactive effects of chemical prophylaxes and treatments will be predictable for hot environments, based on human studies previously conducted at the lab. This is important for current efforts to include heat strain predictions with environmental chemical sensors, to help balance a decision between the risk of some level of chemical threat agent exposure and the expected physiological tolerance an individual adopting mission-oriented protection posture under the existing environmental conditions (Figure 4). In addition to advancing research models to improve the predictions and drive towards prediction of individual variability, USARIEM modelers have been able to react quickly to current needs to provide heat/cold threat assessment tools to warfighters and commanders. For example, an environmental risk "Slide Rule" was developed for Ranger school cadre to read off the reasonable pace time for standard distance runs and road marches according to prevailing heat conditions, reducing serious environmental extremes risk to the Soldiers in training. This past summer, close monitoring of Ranger training events with elevated heat injury risk was explored through the use of a simple ingestible pill-based core temperature measurements in a few sentinel students.



*Fig 4. Evaluation of the heat strain produced in chemical overgarments with Soldier participants exercising on a treadmill in the Doriot climatic chambers. Thermal physiologists at USARIEM have evaluated all chemical pretreatments and personal protective equipment before approval and fielding by the Army.*

#### **Materiel Optimized to Human Tolerances – Biomedical Databases and Models for Virtual Prototyping**

The USARIEM has been instrumental in ensuring that the clothing and equipment developed for warfighters by the Natick Soldier Center is assessed against valid scientific research to determine the physiological cost to the user. For example, metabolic costs associated with backpack and protective equipment designs have been used to guide more efficient

personal equipment designs. The increased energy requirements in cold weather are more related to the hobbling effect of bulky cold weather clothing than to heat production.<sup>19</sup> The design of load carriage equipment, protective gear, and even the tasks themselves can be optimized from these data and evolving models of load carriage (Figure 5).<sup>20,21</sup>



Fig 5. Studies of energy cost produced by movement with various load configurations has led to design guidelines for scientifically optimized Soldier equipment. Many of these studies are conducted in the biomechanics research laboratory shared between USARIEM and the Natick Soldier Center.

In addition, there are many examples of attempts to retrofit equipment, select Soldiers, or even re-engineer Soldiers (through training) to fit and operate equipment that was designed without adequate consideration to the human operator. Some remarkable examples came out of studies in the Defense Women's Health Research Program, with backpacks and safety equipment that were not compatible with female body proportions. Even before this, an entire USARIEM effort in the 1980s was focused on classifying Army jobs by physical demands, and for a brief period in Army history, recruits were steered away from high physical demand job specialties on the basis of a lift strength test. It has been since recognized that attempting to fit individuals to ill conceived equipment and task designs increases injury risk and impairs efficiency for both men and women. A recently completed USARIEM study considered this relationship between occupational strength demands and musculoskeletal injury rates. One military occupational specialty was selected as a representative specialty with very high injury rates (63B, light wheeled vehicle mechanic) to determine if injuries are indeed associated with mismatches between key task requirements and deficient strength capabilities of Soldiers performing the tasks (Figure 6). A separate and specific benefit of this study may be recommenda-

tions for improved design of the Future Combat System over the tasks required for maintenance of the HUMMV that did not fully consider the human element, specifically the physical requirements imposed on the mechanic.

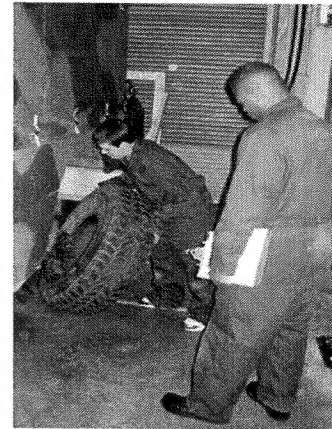


Fig 6. Field study conducted through the USARIEM Medical Research Unit, Fort Bragg. Light-wheeled vehicle mechanics are being studied to determine if injury rates are correlated with mismatches between the strength of the Soldiers and the strength requirements for key occupational tasks. This will determine if occupational strength training and testing may be of importance in heavy strength demand job specialties.

### Improve Physical Capacity Without Injury – Soldiers as Specialized Athletes

Flat feet and underweight eliminated potential Army recruits in the last century. We now know from USARIEM research that individuals with high arches have the highest risk of injury and flat feet could be protective although there is inconsistency even in the evaluation of arch status between assessors.<sup>22</sup> Modern body composition standards have focused on overweight as a marker of fitness habits rather than underweight as an indicator of poor health and inadequate strength. Fat standards have been in place for the past 20 years, although it is entirely possible that we will return to inclusion of underweight standards in the future to ensure minimum lean mass to ensure adequate strength and reduce injuries for common tasks. Biomedically-based standards for entry and retention to the Army have been actively investigated by USARIEM with extensive collaborations in the past with the Naval Health Research Center, San Diego.<sup>23</sup>

There is a common perception that we don't need more research in sports physiology because all the important science is known or is being done elsewhere and, furthermore, all necessary information can be gleaned from popular fitness

magazines. This partly reflects the fact that everyone is an exercise “expert” based on their own anecdotal experience and usually without an appreciation for the potential applications of emerging science such as the discovery of myostatin’s role in regulating muscle satellite cells and the effects of local IGF-1 production on muscle and bone that may accelerate tissue repair and remodeling in the future. Although the entire exercise physiology program at USARIEM is relatively small, this represents a national lead in physical performance research, especially in training studies, with no other federal agency sponsoring significant efforts in optimizing physical performance of healthy individuals, and no other military service currently conducting an organized research program in this area. The influence of USARIEM researchers in the exercise physiology community is highlighted by large representation of our scientists in the professional activities of the American College of Sports Medicine (ACSM), including as senior editor of the primary journal of the ACSM and in the authoring of many of the organizations position statements.

Current USARIEM efforts in physical performance are focused on physical training studies to determine modes of exercise that will provide specific benefits and to simultaneously explore the underlying mechanisms of bone and muscle remodeling that signal both healthy adaptations and maladaptive responses that may lead to muscle injury and stress fracture. Within the past few months, a new TB MED on physical training and injury prevention has been developed, and new guidance to reduce running injuries in basic training has been established for Army-wide implementation in collaboration with CHPPM.<sup>24</sup>

Bone biology is an example of USARIEM’s multidisciplinary and integrated approach to addressing important Army problems, where the way we train, feed, and treat young men and women may, in combination, affect risk of stress fracture and longer term risks of osteoarthritis and osteoporosis. The fundamental principles that are derived from well-designed basic research studies can be particularly useful to scientists trained to recognize breakthrough findings that are relevant to military applications. For example, a discovery about biomechanical stress responses at the cellular level suggests that breaking up physical training into multiple daily sessions might provide more beneficial stimulation to bone than that produced in a single more intensive daily session, and this can now be further tested in a hypothesis-driven study. Monitoring impending risk of injury is also an active area of basic research investigation.<sup>25,26</sup> An overuse injury model that is being developed by JAYCOR in collaboration with USARIEM will further test predictions and helps focus research hypotheses based on existing and emerging bone injury data. In addition to bone remodeling studies, muscle injury and repair mechanisms are being pursued, including related topics that are important to

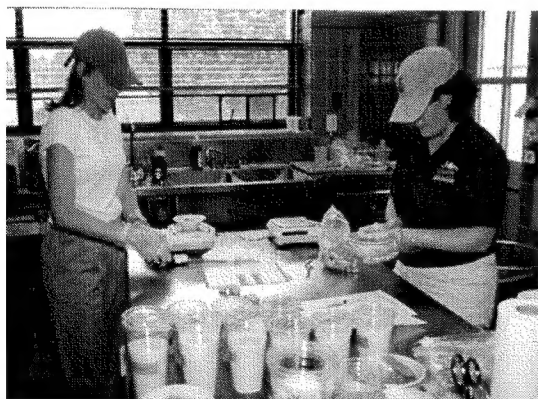
protecting young Soldiers in training such as rhabdomyolysis and exertional heat injury. In addition to the internal efforts of USARIEM scientists, extramural studies are leveraged to assess and improve physical performance on behalf of the Army. One recent Army-sponsored study at Ohio University debunks the concept of a “female athlete triad” syndrome, where women who exercise intensively do not, in fact, shut down their reproductive cycles as long as they reasonably match energy intakes to energy requirements; however, women who surpass a threshold of energy deficit with severe dieting are at increased risk for bone loss.<sup>27</sup> Such highly relevant extramural studies complement and augment the limited capacity of one small Army research lab and, as in this case, can produce immense payoffs in early translation by USARIEM experts to Army policies such as those involving fitness, weight control, and high intensity training.

### **Metabolic Enhancement and Nutritional Stress Countermeasures – the good, the bad, and the ugly**

In WWI, the Army was concerned about defining energy and nutrient requirements for various Soldier cohorts such as units primarily composed of specific ethnic European groups to ensure adequate provisioning of each group. The concept was discouraged by a panel of scientific advisors that formed the nucleus of nutrition research in the U.S., and also founded the Food and Nutrition Board that later became part of the Institute of Medicine. In the past decade, this concept of metabolic tailoring for individuals resurfaced and USARIEM addressed it through a series of studies in collaboration with the Pennington Biomedical Research Center in Baton Rouge, reviewed by the Committee on Military Nutrition Research under the same Food and Nutrition Board. Even Special Forces Soldiers behaved in a highly predictable manner as they exercised to exhaustion, stepping from glycogen metabolism to fat metabolism with greater homogeneity than the most skeptical energy balance scientists had predicted. Other studies explored metabolism and energy requirements in extreme environments ranging from extreme cold in tents in Alaska to high altitude runway construction by SeaBees in Bolivia. The true benefit of this series of studies was to demonstrate that carbohydrate supplementation during work could substantially extend performance. This successfully completed Army STO provided the technical data package to support the fielding of the Hooah bar and ERGO drink, two different forms of carbohydrate supplementation for Soldiers.<sup>28</sup>

At least equally important to creating new options for health and performance of Soldiers is the role of USARIEM experts in protecting the Soldier against perhaps well-intended but bad ideas. Individually tailored rations would have been costly and diverted Army energy to an improvident effort but probably would have created little harm. Similarly,

entrepreneurial fads such as “structured” water and oxygenated water, egg whey proteins, etc. may be expensive and distracting but generally harmless. Other solutions that have been proposed, such as a pure fat diet to provide a compact energy-dense assault ration could be quite harmful, causing serious gastrointestinal distress and, for some Soldiers, chronic problems and performance degradation. The concept that U.S. Soldiers will eat almost anything if they are hungry enough is another common fallacy that is periodically resurfaced to USARIEM nutrition researchers, even though this was addressed long ago in a wide range of nutrition studies on pure gelatin, pemmican, and other specialized diets.<sup>2</sup> During WWII, an Army physician tracked maneuvering troops through the North African desert by following discarded K rations that, although “nutritionally complete” on the basis of the latest science, were “left untouched even by the desert rodents.”<sup>29</sup> Some of the bad ideas in Soldier nutrition emerge where experimental data is lacking, providing a marketing penetration opportunity to any entrepreneur with a reasonable sounding claim. An important research gap currently being addressed under a new Army STO is the protein requirement when inadequate calories are available, such as on a relatively short mission where weight restrictions may prohibit carrying a full load of rations. This problem of providing an optimized and digestible minimum weight and volume supplement rather than leaving the Soldier to field strip rations down to a few random items that they choose to carry was identified as a key research requirement in a 1944 War Department memorandum. Although aspects of this question were addressed in the 1970s at the Jungle Warfare School, only now, with new technologies such as stable isotope labeled substrates and improved understanding of metabolism, can we finally address the protein requirements (Figure 7).<sup>30</sup>



*Fig 7. Food preparation kitchen in the Doriot climatic chambers. Research dieticians prepare specialized meals consisting of precisely characterized homogenates with varying protein content for a study to determine protein requirements of healthy young Soldiers working in a hypocaloric environment.*

Most people would agree that Soldiers should be provided every advantage that biomedical research can safely provide, including supplements and training methods that might be considered unfair in sports competition. However, many of the ergogenic aids that change performance by hundredths of a second and make the difference between a gold medal and no medal have little relevance to success on the battlefield. Thus, substrates such as creatine clearly work but may not provide the kind of advantage that benefits Soldier performance.<sup>31,32</sup> Stimulants such as caffeine clearly work, including at levels that would be banned in elite sports competition as unfair, and is being considered for fielding in gum and food bars (Figure 8).<sup>33</sup> Metabolic triggers such as carnitine do not wreak metabolic havoc with every meal and thankfully do not appear to work in healthy humans, where they might actually damage mitochondria if transport systems and biochemical pathways would actually allow it. Neurochemical precursors such as choline do not provide any measureable benefit and may leave an individual smelling like rotting fish, but tyrosine appears to provide important benefits in mitigating severe stress effects on mood and cognition and is being further investigated in human cold exposure studies.<sup>34</sup> The USARIEM studies have demonstrated the very potent ergogenic benefits produced by methods to boost the oxygen carrying capacity of the blood (for example, intermittent hypoxia training; erythropoietin; autologous blood transfusions) and these might be useful in special cases for elite troops and in high altitude operations.<sup>35,36</sup> The promise of storing water like a camel using glycerol hyperhydration failed to materialize into a clear performance or thermal protection benefit.<sup>37</sup> Antioxidants have been repeatedly investigated in the prevention of delayed onset muscle soreness, at altitude, and in other performance studies, with no clear



*Fig 8. Psychometric research laboratory instrumented for automated marksmanship and vigilance testing. A study participant is being tested for friend-foe discrimination in a sentry duty task that involves distracting stimuli and several hours of concentration. Caffeine sustains judgment over several hours of concentration while common medications such as some antihistamines impair Soldier discrimination and performance.*

benefit to the Soldier; some level of oxidative stress may even be important to stimulating normal processes of adaptation.<sup>38</sup> Investigation of antioxidant benefits in the mitigation of long-term health consequences in Soldiers is likely to continue at USARIEM.

## Conclusions

It's not enough to recruit healthy young men and women and later return them safely to their families; we now try to return them better than when they joined the Army with the promise that they will "be all they can be." With this comes the concept that the Army will accept any healthy recruit and provide them the scientifically sound metabolic and physiological tools for success. The USARIEM research is directed at ensuring that scientific soundness and further ensuring the protection and enhancement of the health and performance of all warfighters. The USARIEM research effort with thrust areas and core capabilities aligned with near and far term applications is captured in Table 5. Current efforts to

understand the fundamental metabolic processes underlying the responses to operational stressors, most importantly the neurophysiological responses that affect cognitive, psychomotor, and emotional status, are critical investments in the health and performance of the future Soldier.<sup>39,40</sup>

## References

1. Pandolf KB, Burr RE (eds.) Medical Aspects of Harsh Environments. Volumes 1 & 2. Washington DC: Office of The Surgeon General, TMM Publications.
2. Horvath SM, Horvath EC. The Harvard Fatigue Laboratory – Its History and Contributions. Englewood Cliffs, NJ: Prentice-Hall, Inc; 1973:p182.
3. Schnakenberg DD. Military nutrition research – a brief history, 1917-1980. *Nutr Hist Notes*. 1986;25:1-4.
4. Robinson S, Turrell ES, Belding HS, Horvath SM. Rapid acclimatization to work in hot climates. *Am J Physiol*. 1943;140:168-176.
5. Sawka MN, Latzka WA, Montain SJ, et al. Physiologic tolerance to uncompensable heat: intermittent exercise, field vs laboratory. *Med Sci Sports Exerc*. 2001;33:422-30.

Research Goals for the Soldier (core capability)	Current	Near-term (for example, STOs*)	Mid-term (current/ planned)	Far-term (basic research)
Own the Environment (Environmental physiology)	Demonstrated feasibility of physiologically-based microclimate cooling	*Develop predictive models and strategies for rapid acclimatization to altitude	*Improve hydration data and monitoring methods to counter dehydration and reduce logistics	Explore genetic markers of susceptibility to environmental injury
Optimize Materiel to Human Tolerances (Biomechanics)	Established biomechanically-based design criteria for load carriage equipment	*Assess neck injury thresholds for helmet design criteria	Study mobility: artificial limbs, extremity body armor, and prototype exoskeleton devices	<i>Integrate biomechanical injury and performance models for virtual design prototyping</i>
Extend Physical Capacity Without Injury (Exercise physiology)	Provided new science-based training guidelines for initial entry training	*Determine specific training strategies for rapid train-up without injury	Develop strategies to eliminate stress fractures in initial entry training	<i>Investigate strategies to enhance bone and muscle repair</i>
Metabolic Enhancement (Nutrition science)	Identified dietary supplements to improve physical task performance	*Determine protein req'ts to sustain mental performance with hypocaloric rations	Develop effective weight management strategies that enhance Soldier readiness	<i>Explore nutrient partitioning strategies to metabolize fat and preserve lean tissues</i>
Monitoring to Prevent "System" Failure (Biomathematical modeling)	Reviewed heat strain decision model for integration with area chemical detectors	*Develop initial capability Warfighter Physiological Status Monitoring system	Expand real time data handling capabilities and analysis of energetic for Soldier Status monitoring	Define approaches to noninvasive monitoring of cognitive status and readiness
Post Deployment Neurological Health (Neuro-epidemiology)	Compared effectiveness of neuropsychological health monitoring strategies in deployment	Determine methods to assess neurological health effects of materiel (permethrin, JP8)	Identify important interactions of deployment stressors for better neuroprotection	<i>Explore behavioral strategies to regulate neurochemistry to optimize resilience</i>
Ensure Effectiveness of Protective Equipment (Oxidative and Inflammatory Stress)	Validated threshold for shoulder injury from weapon recoil systems	<i>*Develop new injury-based assessment system for body armor protection</i>	Identify biochemical and physiological markers to assess tissue injury	Explore intrinsic antioxidant protection against mechanical and toxic hazards

\*Science and Technology Objective (STO): italics signify a USARIEM planned and/or current extramural effort

Table 5. Examples of Completed, In Progress, and Future Research Objectives for Metabolic Enhancement of the Soldier

6. Kolka MA, Latzka WA, et al. Effectiveness of revised fluid replacement guidelines for military training in hot weather. *Aviat Space Environ Med.* 2003;74:242-246.
7. Cheuvront SN, Kolka MA, et al. Efficacy of intermittent, regional microclimate cooling. *J Appl Physiol.* 2003;94:1841-8.
8. Young AJ, Castellani JW, et al. Exertional fatigue, sleep loss, and negative energy balance increase susceptibility to hypothermia. *J Appl Physiol.* 1998;85:1210-7.
9. Tikuisis P, Gonzalez RR, Pandolf KB. Thermoregulatory model for immersion of humans in cold water. *J Appl Physiol.* 1988;64:719-27.
10. Johnson TS, Rock PB, et al. Prevention of acute mountain sickness by dexamethasone. *N Engl J Med.* 1984;310:683-6.
11. Sonna LA, Wenger CB, et al. Exertional heat injury and gene expression changes: a DNA microarray analysis study. *J Appl Physiol.* 2004;96:1943-53.
12. Sonna LA, Sharp MA, Knapik JJ, Cullivan M, et al. Angiotensin-converting enzyme genotype and physical performance during U.S. Army basic training. *J Appl Physiol.* 2001;91:1355-63.
13. Hoyt RW, Reifman J, Coster TS, Buller MJ. Combat medical informatics: present and future. *Proc AMIA Symp.* 2002;335-339.
14. Hoyt RW, et al. Ambulatory foot contact monitor to estimate metabolic cost of human locomotion. *J Appl Physiol.* 1994;76:1818-22.
15. Weyand PG, Kelly M, et al. Ambulatory estimates of maximal aerobic power from foot-ground contact times and heart rates in running humans. *J Appl Physiol.* 2001;91:451-8.
16. Nelson N, Eichna LW, Horvath SM, Shelley WB, Hatch TF. Thermal exchanges of man at high temperatures. *Am J Physiol.* 1948;151:626-652.
17. Cadarette BS, et al. Cross validation of USARIEM heat strain prediction models. *Aviat Space Environ Med.* 1999;70:996-1006.
18. Gonzalez RR, et al. Heat strain models applicable for protective clothing systems: comparison of core temperature response. *J Appl Physiol.* 1997;83:1017-32.
19. Consolazio CF, Schakenberg DD. Nutrition and the responses to extreme environments. *Fed Proc.* 1977;36:1673-8.
20. Holt KG, et al. Increased musculoskeletal stiffness during load carriage at increasing walking speeds maintains constant vertical excursion of the body center of mass. *J Biomech.* 2003;36:465-71.
21. Patton JF, Bidwell TE, et al. Energy cost of wearing chemical protective clothing during progressive treadmill walking. *Aviat Space Environ Med.* 1995;66:238-42.
22. Cowan DN, Jones BH, Robinson JR. Foot morphologic characteristics and risk of exercise-related injury. *Arch Fam Med.* 1993;2:773-7.
23. Sharp MA, Patton JF, Knapik JJ, Hauret K, et al. Comparison of the physical fitness of men and women entering the U.S. Army: 1978-1998. *Med Sci Sports Exerc.* 2002;34:356-63.
24. Knapik JJ, et al. Guidance for Ability Group Run Speeds and Distances in Basic Combat Training. USACHPPM Project No 12-HF-5772A-03. USACHPPM, USAFPFS, USARIEM. 2004;pp. 26.
25. Sheehan KM, Murphy MM, Reynolds K, et al. The response of a bone resorption marker to marine recruit training. *Mil Med.* 2003;168:797-801.
26. Nindl BC, Kellogg MD, Khosravi MJ, et al. Measurement of insulin-like growth factor-I during military operational stress via a filter paper blood spot assay. *Diabetes Technol Ther.* 2003;5:455-61.
27. Loucks AB, Thuma JR. Luteinizing hormone pulsatility is disrupted at a threshold of energy availability in regularly menstruating women. *J Clin Endocrinol Metab.* 2003;88:297-311.
28. Friedl KE, Hoyt RW. Development and biomedical testing of military operational rations. *Ann Rev Nutr.* 1997;17:51-75.
29. Bean WB. The ecology of the Soldier in WWII. Medical Bulletin of the U.S. Army, Europe. 1985;42:20-25.
30. Committee on Military Nutrition Research. Food and Nutrition Board. Institute of Medicine. The Role of Protein and Amino Acids in Sustaining and Enhancing Performance. Washington DC: National Academy Press; 1999.
31. Warber JP, Tharion WJ, et al. The effect of creatine monohydrate supplementation on obstacle course and multiple bench press performance. *J Strength Cond Res.* 2002;16:500-8.
32. Smith SA, et al. Use of phosphocreatine kinetics to determine the influence of creatine on muscle mitochondrial respiration: an in vivo <sup>31</sup>P-MRS study of oral creatine ingestion. *J Appl Physiol.* 2004;96:2288-92.
33. Tharion WJ, Shukitt-Hale B, Lieberman HR. Caffeine effects on marksmanship during high-stress military training with 72 hour sleep deprivation. *Aviat Space Environ Med.* 2003;74:309-14.
34. Shukitt-Hale B, Stillman MJ, Lieberman HR. Tyrosine administration prevents hypoxia-induced decrements in learning and memory. *Physiol Behav.* 1996;59:867-71.
35. Sawka MN, Young AJ, et al. Erythrocyte reinfusion and maximal aerobic power. An examination of modifying factors. *JAMA.* 1987;257:1496-9.
36. Sawka MN, Joyner MJ, et al. American College of Sports Medicine position stand. The use of blood doping as an ergogenic aid. *Med Sci Sports Exerc.* 1996;28:i-viii.
37. Latzka WA, Sawka WN, Montain SJ, et al. Hyperhydration: tolerance and cardiovascular effects during uncompensable exercise-heat stress. *J Appl Physiol.* 1998;84:1858-64.
38. Askew EW. Work at high altitude and oxidative stress: antioxidant nutrients. *Toxicology.* 2002;180:107-19.
39. Committee on Military Nutrition Research. Monitoring Metabolic Status: Predicting Decrements in Physiological and Cognitive Performance. Washington DC: National Academy Press; 2004;p 476.
40. McBride SA, Johnson RF, Merullo DJ, Bartow RE Jr. Effects of the periodic administration of odor or vibration on a 3-hr. vigilance task. *Percept Mot Skills.* 2004;98:307-18.

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